

Construction Technology and Digital Quality Control for A Low-Rise Building with A Pultruded Composite Frame And 3d-Printed Walls

BIM-Oriented Production Workflow, 4D Planning, Process Monitoring, And A Digital Building Passport

 Dilshod Bakhodirovich Akbarov

Tashgiprogor LLC, Tashkent, Uzbekistan; Chief Project Engineer; M.Sc. in Production of Building Materials, Products and Structures, Uzbekistan

 Khusnitdin Akhrarovich Akramov

Department of Technology of Building Materials and Structures, Tashkent University of Architecture and Civil Engineering, Tashkent, Uzbekistan; Doctor of Technical Sciences, Professor, Uzbekistan

Received: 12 August 2026 | Received Revised Version: 04 September 2026 | Accepted: 16 September 2026 | Published: 10 October 2026

Volume 08 Issue 10 2026 | Crossref DOI: 10.37547/tajet/Volume08Issue10-04

Abstract

This study investigates the construction technology for a two-story low-rise building in which the load-bearing system is assembled from factory-fabricated pultruded glass-fiber-reinforced polymer (GFRP) profiles, while the external enclosures comprise three-layer 3D-printed walls with a polystyrene-concrete core. The production task extends well beyond conventional wall printing: the digital model, fabrication and marking of GFRP components, surveying, installation of deformation-decoupled connections, generation of machine toolpaths, material delivery, installation of embedded components, core filling, geometric quality control, and transfer of as-built data into the digital building passport must all be coordinated.

A BIM-oriented methodology is developed around a continuous digital thread: “requirement—model object—technological operation—inspection record—acceptance decision.” The information environment is organized in accordance with the ISO 19650 series; open exchange is described through IFC under ISO 16739-1:2024; the level of information need is defined under ISO 7817-1:2024; and construction-object data are structured with reference to ISO 23386 and ISO 23387:2025. Qualification of the additive process follows the logic of ISO/ASTM 52939:2023. A persistent identifier is proposed for each element, linking its geometry, material, batch, toolpath, printing parameters, photographs, point cloud, test results, and as-built revision.

For the demonstration building measuring 10.8×7.2 m, with two stories and 20% openings, the net printed-enclosure area is 172.8 m². The calculated volume of print mortar, including local cross-ties, is 11.61 m³, and the volume of the polystyrene-concrete core is 31.59 m³. At a layer height of 20 mm, bead width of 45 mm, nozzle speed of 120 mm/s, and overall equipment effectiveness OEE = 0.742, the effective production rate is 0.289 m³/h and the printing duration is approximately 40.2 h. An 18-day demonstration 4D schedule is proposed for the superstructure, including frame assembly, printing of both stories, inspection hold points, core filling, roof installation, and compilation of the digital passport.

The scientific novelty lies in integrating BIM information management, DfMA preparation of the composite frame, process calculation for 3D printing, statistical process control, point-cloud-based geometric verification, and a system of release

quality gates. It is shown that testing specimen strength alone is insufficient: wall reproducibility depends on the combined control of flow rate, speed, bead geometry, interlayer interval, green strength, embedded-component position, and preservation of free travel in the movement-accommodating connections. A verification program is established from material qualification and trial printing through a pilot module and the as-built building model.

Keywords: Construction 3D printing; pultruded glass-fiber-reinforced polymer; BIM; common data environment; IFC; level of information need; DfMA; 4D model; digital thread; quality control; computer vision; point cloud; OEE; statistical process control; digital passport.

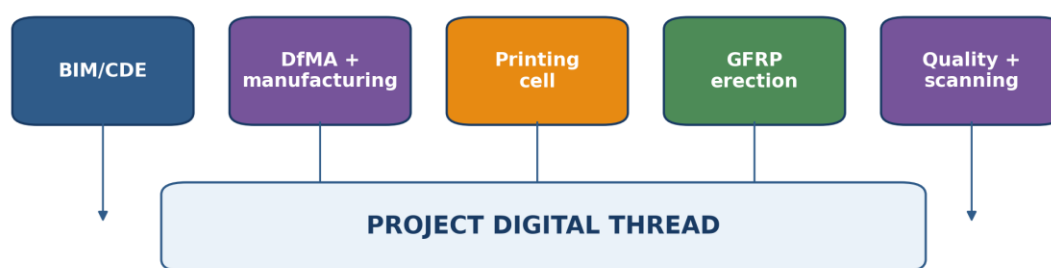
© 2026 Dilshod Bakhodirovich Akbarov, & Khusnitdin Akhrarovich Akramov. This work is licensed under a Creative Commons Attribution 4.0 International License (CC BY 4.0). The authors retain copyright and allow others to share, adapt, or redistribute the work with proper attribution.

Cite This Article: Dilshod Bakhodirovich Akbarov, & Khusnitdin Akhrarovich Akramov. (2026). Construction Technology and Digital Quality Control for A Low-Rise Building with A Pultruded Composite Frame And 3d-Printed Walls BIM-Oriented Production Workflow, 4D Planning, Process Monitoring, And A Digital Building Passport. The American Journal of Engineering and Technology, 8(10), 56–88. <https://doi.org/10.37547/tajet/Volume08Issue10-04>

1. Introduction

Construction 3D printing is evolving from an isolated operation for forming cementitious geometry into part of a complex production system. A building requires not only continuous extrusion, but also design compatibility

of the printed shell with the foundation, frame, openings, building services, thermal-insulation fill, and movement-accommodating connections. Any change in toolpath, mixture composition, or embedded-component position must be reflected in the as-built model and linked to a decision on the suitability of the element [15–17, 28–37].



requirement -> model object -> operation -> control record -> acceptance decision -> digital passport

Design premise: a construction operation is complete only after controlled parameters and the acceptance decision have been recorded.

Figure 1 — Integrated digital and production concept for construction of the hybrid 3D-printed building

In the structural system considered, the load-bearing and enclosure functions are separated. The pultruded GFRP frame resists vertical and lateral loads, while the three-layer printed walls are nonstructural with respect to the global response of the frame. Their self-weight is transferred through bottom supports, out-of-plane actions through anchors, and slotted holes and movement joints preserve relative in-plane movement. The

construction technology must physically realize this analytical assumption: the specified free travel must not be lost because of mortar, finishes, installation offset, or incorrect bolt positioning.

Pultruded profiles provide highly repeatable geometry and are well suited to factory preparation in accordance with Design for Manufacturing and Assembly principles. Holes, cuts, and local connection zones are nevertheless

sensitive to processing quality. Frame production therefore requires digital cutting schedules, identification of every component, inspection of edges and holes, surface protection, fastener kitting, and survey verification of the assembled three-dimensional configuration [22–24].

The printed cementitious shell, by contrast, is formed directly on site or as a large module and depends on the time-dependent state of the material. Pump delivery, nozzle speed, layer height, bead width, interlayer interval, temperature, humidity, and wind action form an interdependent system. Identical digital geometry does not guarantee an identical result unless the process context is recorded. For this reason, ISO/ASTM 52939:2023 treats qualification of additive construction as a process-based activity encompassing the operations within the print cell [15].

Building information modeling provides the basis for coordinating the participants. The ISO 19650 series defines processes for exchange, version control, and organization of information; IFC provides an open data schema; the level of information need limits both missing and excessive information; and data templates enable machine-readable descriptions of object properties [5–14]. For construction 3D printing, this foundation must be extended to include toolpath, layer, mixture batch, control coupon, and actual deviation from the model.

The relevance of the topic to the Republic of Uzbekistan is reinforced by the developing regulatory and organizational framework for digital construction. Presidential Decree No. UP-151 of August 28, 2023 established responsibilities for implementing CDE, ERP, and BIM in the construction industry, while Resolution No. 231 of April 23, 2024 provides for development of ShNK 1.05.01 on information modeling in construction. Resolution No. PQ-104 of March 13, 2026 provides for simplified review of certain sections of predesign documentation prepared using BIM and for development of a unified exchange format between the expert-review center and design organizations [1–4].

A practical problem is that the BIM model, robot control file, mixture log, scan results, and concealed-work inspection records often exist independently. Under such an arrangement, it is impossible to demonstrate which exact set of parameters was used for a specific wall region. This study proposes a digital thread in which every construction component and production batch has a persistent identifier, and progression to the next operation is permitted only after a formalized quality gate has been passed.

2. State of the Art and Research Gap

2.1. From the BIM model to construction 3D printing

Current studies propose workflows that include wall segmentation, geometry transfer, adjustment of openings and widths, toolpath generation, simulation of manipulator reachability, and transfer of data to the control system. Most schemes, however, focus on the geometric transition from “model to print” and describe the return of actual process parameters to the information model to a lesser extent [25–27].

For manufacturing readiness, a BIM object must contain not only architectural form, but also process attributes: permissible print orientation, layer height, nozzle type, contour sequence, stop locations, coordinates of embedded components, mixture-recipe identifier, required interlayer interval, and inspection criteria. Such an object is closer to a digital production instruction than to a conventional working-documentation element.

Open exchange through IFC is important for long-term independence of the data from a specific software product. At the same time, the robot toolpath is normally stored in a specialized format that does not replace the building model. Dual representation is therefore required: a neutral container for requirements and results, and a machine file unequivocally linked to the model revision and a verification signature.

2.2. Control of extrusion-printing parameters

Material and process studies show that pumpability, extrudability, and buildability must be considered together. Increasing speed at constant flow reduces the bead cross-sectional area; increasing flow at constant speed increases bead width and the risk of bulging; a longer interlayer interval may reduce bond strength; and an excessively rapid build-up increases stress in the lower early-age layers [28–36].

Roussel, Perrot, and subsequent researchers related the stability of a printable wall to structuration and the early-age strength of the cementitious system. For production control, it is important not only to measure a mixture property before work begins, but also to confirm that it remains within the qualified range throughout the processing window [33–34].

A review of control parameters shows that both inputs—composition, temperature, humidity, speed, and flow rate—and outputs—bead geometry, continuity, surface defects, settlement, wall deviation, and condition of the interlayer interface—must be recorded [37–45].

2.3. Automated monitoring and computer vision

Computer-vision systems can measure extrudate width and height, classify defects, track deformation, and

provide feedback for adjustment of flow rate or speed. Studies by Kazemian, Lao, and other researchers demonstrate the transition from passive observation to closed-loop control [38–43].

Automatic correction must nevertheless remain within the qualified processing window. An algorithm may compensate for small deviations, but must not conceal an incorrect mixture recipe, pump failure, coordinate shift, or loss of buildability. Such events require a safe stop, registration of a nonconformance, and a decision by the responsible specialist.

After printing, a point cloud or RGB-D survey can be used to compare the actual surface with the design model. Geometric verification is especially important at interfaces with the GFRP frame, openings, and sliding anchors, where accumulated small deviations may consume the design clearance [42–45].

2.4. Printed-material quality and interlaboratory reproducibility

The quality-control roadmap for hardened printed concrete emphasizes the need to account for sampling

direction, layer orientation, process interval, extraction method, and curing regime. Properties of a conventionally cast specimen are not automatically representative of a layered element [44–47].

Interlaboratory studies by RILEM TC 304-ADC demonstrated substantial scatter among materials, equipment, and test methods. This confirms that a mixture data sheet without process-specific information is insufficient. Each project requires its own qualification matrix: “material—equipment—geometry—operating regime—test” [46–48].

2.5. Research gap

The literature provides separate solutions for BIM integration, rheology, printability, computer vision, point clouds, and control of hardened properties. The missing link is a unified methodology for a hybrid building that connects the factory-produced GFRP frame, printed enclosure system, deformation-decoupled connections, 4D schedule, and digital evidence base for acceptance.

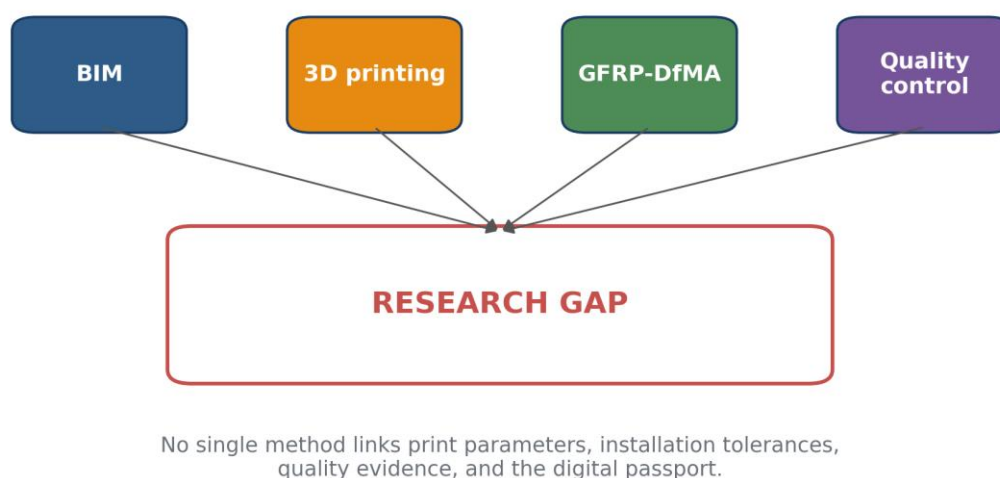


Figure 2 — Research gap among BIM, the additive process, the DfMA composite frame, and quality control

Table 1 — Research gap and the proposed approach to addressing it

Problem	Typical simplification	Proposed solution
Geometry transfer	Export of the model to a machine format without traceability	Link the control file to the BIM revision and a digital signature
Printing parameters	Average values in the shift log	Data stream linked to time, layer, wall, and batch

Problem	Typical simplification	Proposed solution
GFRP quality	Material certificate without component identification	Unique profile ID, hole map, edge photographs, and tightening-torque record
Embedded components	Visual inspection only after completion	Inspection hold point, coordinate verification, and model record
Wall geometry	Selective tape measurements	Point cloud, deviation map, and verification of critical interfaces
Movement-accommodating connections	Concealed-work certificate without a travel check	Measured free travel, photographs, marking, and prohibition of slot filling
Acceptance	Disconnected test reports	Release quality gates G0–G5 and a digital passport

3. Objective, Tasks, and Scientific Novelty

The objective of the study is to develop an integrated construction technology for a low-rise building with a pultruded composite frame and 3D-printed walls that provides digital traceability of design requirements, production parameters, inspection results, and the as-built condition of the facility.

The following tasks are addressed to achieve this objective:

- define the structure of the common data environment and the requirements for information containers at the design, production-preparation, construction, and handover stages;
- develop an object and identification scheme for profiles, connections, wall zones, mixture batches, layers, embedded components, and control specimens;
- establish a DfMA workflow for factory preparation of the GFRP frame and a BIM-oriented workflow for print preparation;
- calculate material volumes, toolpath length, production rate, printing duration, and equipment effectiveness;

- develop a work sequence and 4D schedule coordinating frame erection, printing, core filling, building-services penetrations, and inspection hold points;
- establish a quality plan and methods for incoming, in-process, and acceptance inspection, including statistical control and scanning;
- assess risks using FMEA and define conditions requiring a safe process stop;
- develop a technology-qualification program and define the contents of the pilot building's digital passport.

The scientific novelty lies in treating every physical construction element as the outcome of a controlled information-and-production process. Acceptance applies not only to geometry or strength, but to an interconnected set comprising the approved model revision, qualified material batch, process log, inspection images, measurement results, nonconformance disposition, and as-built position. For deformation-decoupled connections, the retained kinematic function—free travel—is additionally recorded as a measurable quality parameter.

Principal process hypothesis

An operation is considered complete only when the physical result has been achieved, all mandatory data have been recorded, the inspection criterion has been satisfied, and the responsible person has changed the information-container status to “approved/suitable for the next stage.”

4. Building Under Study and Boundaries of the Process Model

4.1. Structural configuration

A two-story residential module measuring 10.8×7.2 m, with a story height of 3.0 m, is considered. The frame

grid is 3.6×3.6 m. The columns, beams, and diagonal braces are made of pultruded GFRP profiles. The three-layer wall comprises two 30 mm printed shells and a 190 mm polystyrene-concrete core. Bottom supports transfer the wall mass, top and side anchors provide out-of-plane

restraint, and slotted holes permit relative in-plane movement.

Table 2 — Geometric parameters of the demonstration building

Parameter	Value	Note
Plan dimensions	10.8 × 7.2 m	Adopted from Articles 1–5
Number of stories / height	2 / 6.0 m	3.0 m per story
Column grid	3.6 × 3.6 m	Coordination module
External-wall perimeter	36.0 m	Excluding internal partitions
Gross wall area	216.0 m ²	Perimeter × height
Opening ratio	20 %	Demonstration value
Net printing area	172.8 m ²	After deduction of openings
Wall build-up	30 + 190 + 30 mm	Printed shell + core + shell

4.2. Approximate production quantities

The volume of printed material is determined from the area of the two shells and an additional factor for local cross-ties. The 12% factor is used solely for demonstration and must be replaced by quantities

$$V_p = A_w \cdot (t_o + t_i) \cdot (1 + k_r) \quad (1)$$

V_p is the volume of print mortar; A_w is the net wall area; t_o and t_i are the shell thicknesses; and k_r is the proportion of cross-ties and local thickenings.

$$V_c = A_w \cdot t_c - V_r \quad (2)$$

V_c is the volume of the polystyrene-concrete core; t_c is the core thickness; and V_r is the volume of internal cementitious cross-ties.

extracted from the actual BIM model. The polystyrene-concrete core is calculated from the net thickness after deducting the cross-ties and embedded-component zones.

Table 3 — Calculated material volumes and masses

Parameter	Calculated value	Status
Volume of the two shells	10.37 m ³	Geometric
Volume of local cross-ties	1.24 m ³	12% of shell volume
Total volume of print mortar	11.61 m ³	Demonstration value
Volume of polystyrene-concrete core	31.59 m ³	After deduction of cross-ties
Mass of printed material	24.4 t	$\rho = 2,100 \text{ kg/m}^3$
Mass of core fill	17.4 t	$\rho = 550 \text{ kg/m}^3$

4.3. Scope of the study

The process model includes preparation of digital data, factory processing of GFRP profiles, surveying, frame

assembly, organization of the print cell, mixture preparation and delivery, printing of the shells, installation of embedded components, core filling,

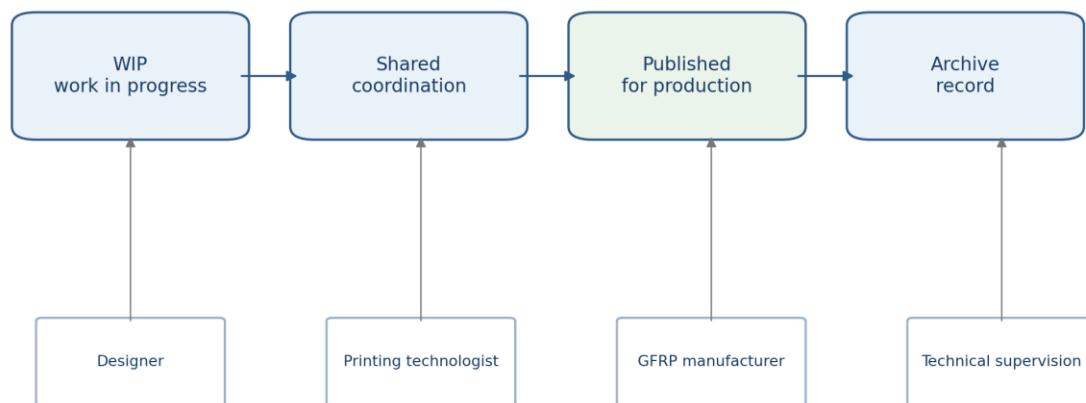
sealing of movement joints, geometric verification, and generation of the as-built model. Detailed technologies for the foundation, roof covering, finishes, and building-services equipment are addressed only insofar as they interface with the frame and printed wall.

5. Information Model and Project Digital Thread

5.1. Common data environment and information states

Information is organized in accordance with the ISO 19650 logic: data are created in the “work in progress”

area, issued for coordination in the “shared” area, published for production after verification, and subsequently archived. Transition between states is a controlled procedure rather than simple file copying [5–8].



Each information container has an author, suitability status, revision, date/time, and linked model objects.

Figure 3 — States of information containers in the common data environment

Table 4 — Minimum attributes of an information container

Attribute	Purpose	Example
Unique code	Unambiguous identification	UZ3DP-B01-PIM-W07-R03
Name	Clear description of content	Toolpath for wall W07 shell
Author/organization	Responsibility for issue	Printing technologist
Suitability status	Permitted use	S3 — suitable for production
Revision	Change control	R03
Date/time	Chronology	2026-07-21 14:30
Linked objects	Traceability	W07, EMB-04, MIX-12
Checksum	File integrity	SHA-256/system hash

5.2. Object hierarchy and identifier system

Each object is assigned a persistent identifier that remains unchanged when data are transferred between software applications. The recommended structure includes the project, building, level, system, sequential

number, and record-type codes. For example, UZ-3DP-B01-L02-W07-SH-A denotes external shell A of wall W07 at Level 2. A process record is supplemented with the batch code and time interval.

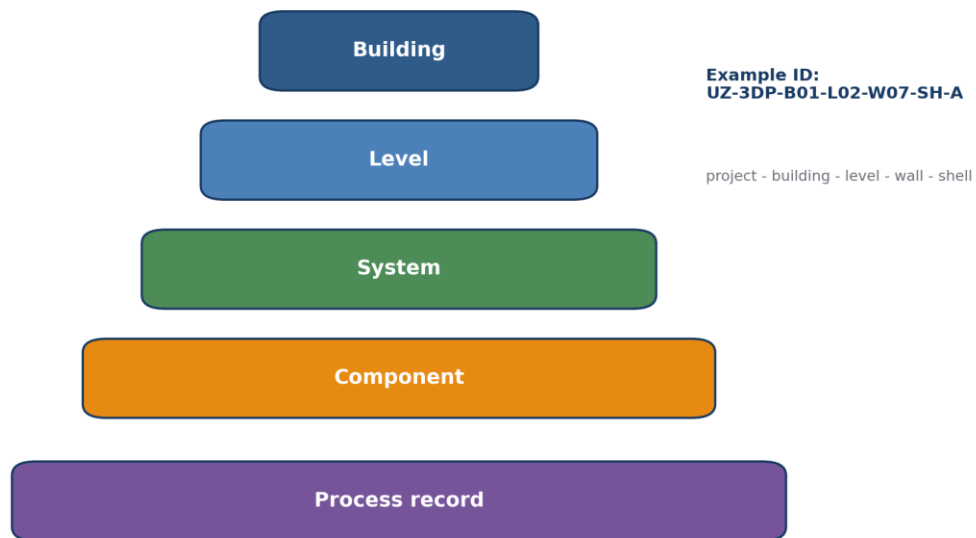


Figure 4 — Digital-thread object hierarchy and example of a persistent identifier

Table 5 — Example classes of digital-model objects

Class	Examples	Mandatory process properties
GFRP profile	Column, beam, brace	Manufacturer, batch, section, length, hole map, mass
Connection	U1–U6	Bolts, washers, sleeves, torque/preload, orientation, free travel
Printed shell	SH-A, SH-B	Recipe, layer, width, height, toolpath, speed, flow rate
Polystyrene-concrete core	CORE	Density, batch, volume, lift height, temperature
Embedded component	EMB	Coordinate, type, before/after photographs, link to anchor
Control specimen	CPN	Sampling location and time, orientation, test method
Inspection record	INS	Parameter, value, tolerance, inspector, decision
Nonconformance	NCR	Description, cause, containment, corrective action, closure

5.3. Level of information need

ISO 7817-1:2024 requires information to be specified in the amount necessary for a particular purpose. For a printed wall, excessive detail at an early

stage is as detrimental as insufficient information before production. The geometric, alphanumeric, and documentary information requirements are therefore assigned at defined control points [10].

Table 6 — Level of information need by project stage

Stage	Geometry	Attributes	Documents
Concept	Overall dimensions, print zones, openings	System type, mass, analytical role	Design brief
Design	Wall layers, connections, embedded components	Materials, tolerances, loads, inspection classes	Calculations and specifications
Production preparation	Segments, toolpaths, stop points	Speed, flow rate, layer, recipe, batch IDs	BEP, quality plan, WPS-like printing procedure specification
Construction	Current model and coordinates	Actual parameters and statuses	Logs, photographs, reports, NCRs
Handover	As-built geometry	Serial numbers, properties, maintenance	Digital passport and instructions

5.4. Open exchange and data templates

ISO 16739-1:2024 defines the open IFC format for exchange of life-cycle data, while ISO 23387:2025 establishes the concept of data templates for machine-

interpretable object descriptions. For process parameters without a standard property set, a project-specific set, Pset_3DCP_Process, is proposed; it is documented in the data dictionary and linked to the IFC object [9, 11–14].

Table 7 — Proposed Pset_3DCP_Process property set

Property	Type	Unit	Purpose
LayerHeight	Number	mm	Target layer height
BeadWidth	Number	mm	Target bead width
NozzleSpeed	Number	mm/s	Travel speed
VolumeFlow	Number	m ³ /h	Volumetric flow rate
InterlayerTimeMax	Number	min	Maximum permitted interval
MixBatchID	String	—	Batch identifier
ToolpathRevision	String	—	Control-toolpath revision
GreenStrengthGate	Number	kPa	Minimum green strength/resistance
ScanReportURI	URI	—	Point-cloud comparison report
AcceptanceStatus	Enumeration	—	Accepted/conditional/rejected

6. DfMA Preparation of the Frame and BIM-Oriented Print Preparation

6.1. Factory preparation of GFRP components

Pultruded profiles should be delivered to site in the most complete condition practicable. The cutting model defines length, orientation, holes, cutouts, and marking.

After processing, the component is cleaned; the edges are inspected for delamination; holes are checked with gauges; exposed surfaces are protected using a manufacturer-recommended compound; and the component code is applied using durable marking and a QR tag.

Table 8 — Factory-preparation workflow for a GFRP profile

Operation	Controlled parameter	Record
Profile receipt	Batch, section, straightness, surface defects	Incoming-inspection report and photographs
Cutting	Length, squareness of end face	Actual dimension
Drilling	Diameter, coordinate, edge distance	Hole map
Edge finishing	Burrs, delamination, chipping	Visual inspection
Protection of exposed cuts	Compound type, coating continuity	Compound batch and photographs
Marking	Unique ID and installation orientation	Kitting register
Kitting	Fasteners, washers, sleeves, cover plates	Packing list

6.2. Transition from model to toolpath

Print preparation begins not with STL export, but with verification of the construction element's production suitability. The wall is segmented according to the equipment work envelope, continuous-pass length,

openings, embedded-component locations, construction joints, and permissible layer-cycle time. The toolpath must ensure continuity, minimize nonprinting travel, and provide nozzle access without collision with the frame.

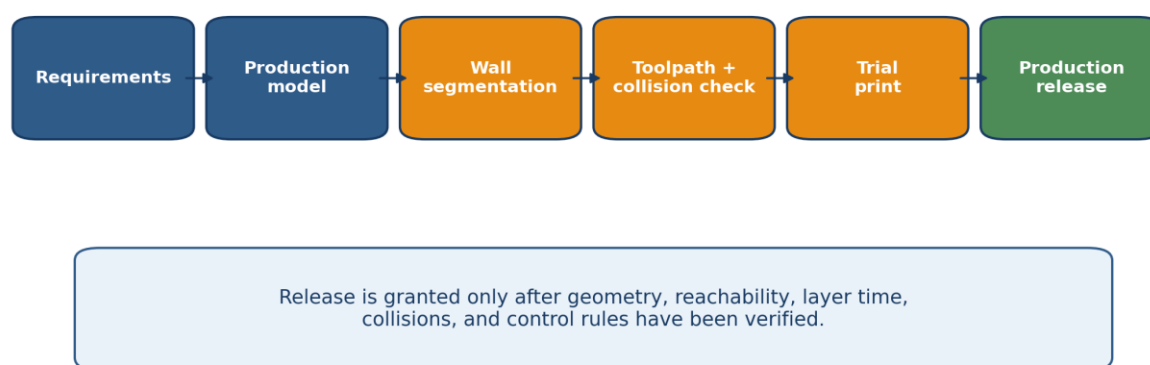


Figure 5 — Controlled workflow from information requirements to production release

Segmentation accounts for openings, construction joints, embedded components, and nozzle access

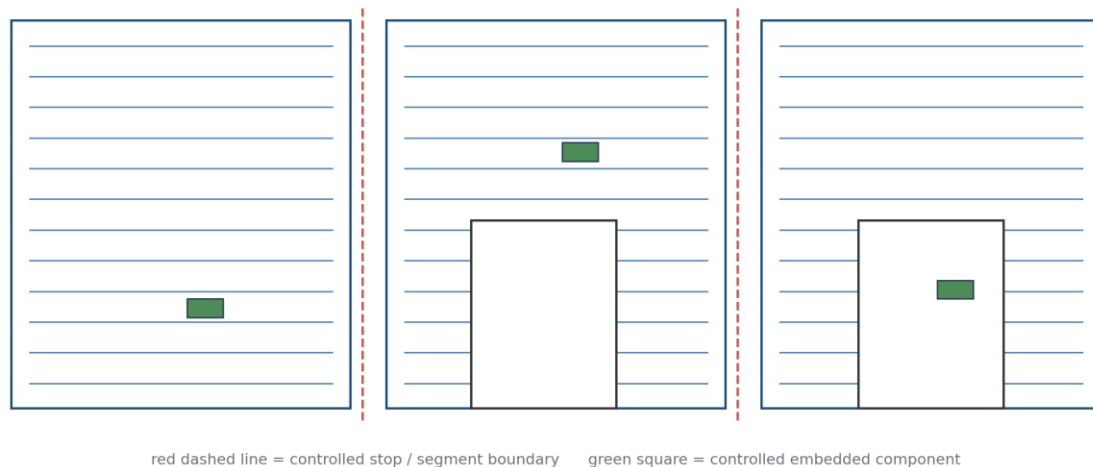


Figure 6 — Principle for segmenting the printed-shell toolpath around openings and embedded components

Table 9 — Control-toolpath checks before release

Check	Criterion	Output
Closure/continuity	No discontinuities other than designated stops	Automated report
Radius of curvature	Not less than the qualified value for the nozzle and mixture	Simulation report
Collisions	No intersection with the frame, supports, or enclosure	collision check
Reachability	The manipulator reaches every point without singularity	robot simulation
Layer time	Does not exceed the qualified interlayer interval	Cycle calculation
Embedded-component coordinates	Consistent with the connection model and installation tolerances	Point schedule
Revision	Matches the published model	Digital signature

6.3. Organization of the construction print cell

The print cell includes the working envelope of the robot or gantry system, the mixing-and-pumping unit, delivery lines, control station, specimen-preparation area, washout area, and safe personnel routes. External

materials and GFRP components must not enter the protected equipment-motion zone during the automatic cycle. Datum-point positions are established by survey and verified using a dry-run toolpath without material.

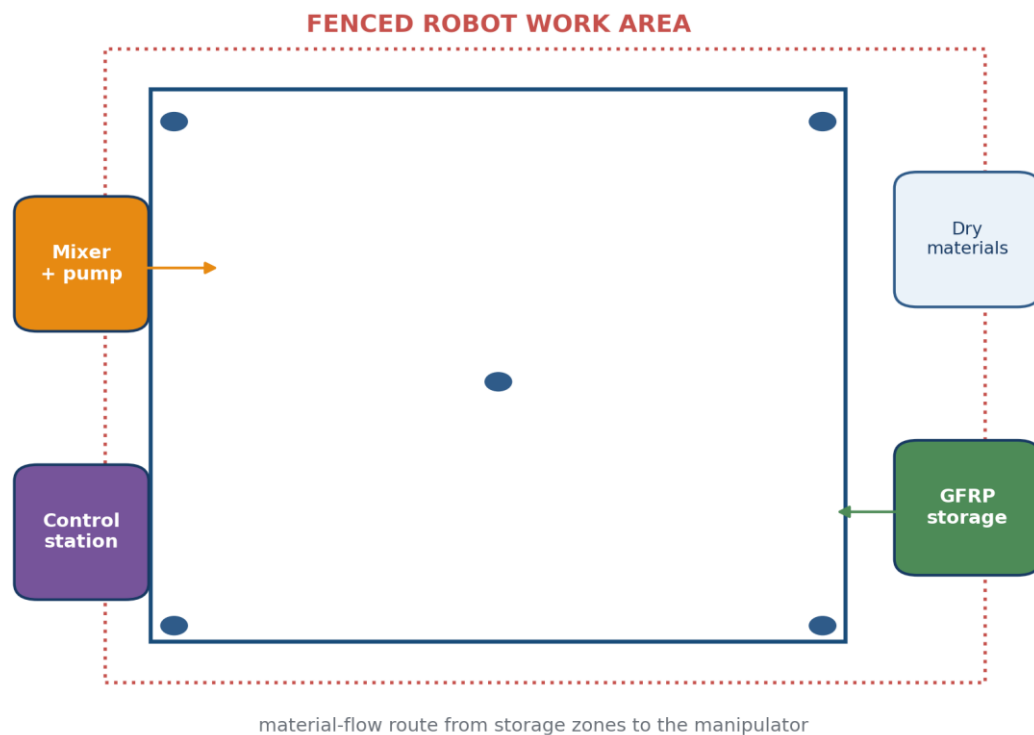


Figure 7 — Schematic layout of the print cell, material areas, and inspection zone

Table 10 — Minimum equipment configuration of the print cell

Subsystem	Function	Pre-shift check
Robot/gantry system	Nozzle positioning	Zero point, brakes, guarding, emergency stop
Mixer	Repeatable mixture preparation	Cleanliness, dispensers, mixing time
Pump and hose	Continuous material delivery	Pressure, leak tightness, wear, blockage
Nozzle/extruder	Bead formation	Dimensions, orientation, distance to the preceding layer
Weather station	Temperature, humidity, wind	Operability and time synchronization
Cameras/depth sensors	Geometric monitoring	Calibration and optical cleanliness
Surveying system	Registration to building coordinates	Verification of control points
Data system	Logging and redundancy	Time, memory, communication channel, backup recording

6.4. Qualification trial print

Before printing the wall, a control specimen is printed that reproduces a straight section, a corner, a stop/restart, an embedded component, and the maximum design height of a local continuous build. The trial print confirms compatibility of the material batch, equipment,

operator, software, and site conditions. Release for production printing is granted after verification of bead geometry, absence of discontinuities, stable material delivery, buildability, and preparation of control specimens.

7. Production-Rate Calculation and Process Constraints

7.1. Relationship among flow rate, speed, and bead geometry

As a first approximation, the volumetric flow rate equals the bead cross-sectional area multiplied by nozzle travel

$$Q = k_f \cdot b \cdot h \cdot v \quad (3)$$

Q is the volumetric flow rate; k_f is the bead shape factor; b is the width; h is the layer height; and v is the

speed. The actual shape differs from a rectangle and depends on compression, distance to the preceding layer, and rheology; the equation is therefore used to establish an initial operating point, while the shape factor is refined by trial printing.

nozzle speed. The demonstration calculation uses $k_f = 1.0$.

Table 11 — Baseline printing parameters

Parameter	Symbol	Value
Layer height	h	20 mm
Bead width	b	45 mm
Nozzle speed	v	120 mm/s
Theoretical flow rate	Q	0.389 m ³ /h
Number of layers over 6 m	N	300
Total toolpath length	L_p	12.90 km
Average layer length	L_l	43.0 m

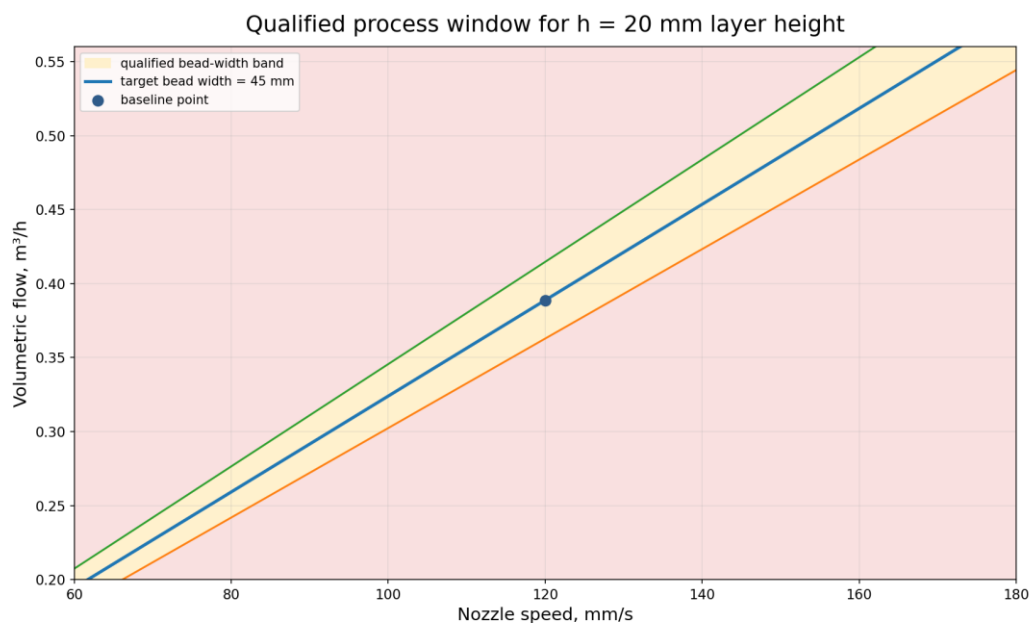


Figure 8 — Calculated processing window for speed and flow rate as a function of bead width

7.2. Layer-cycle duration

$$t_l = L_l / v + t_c + t_s \quad (4)$$

t_l is the layer-cycle duration; L_l is the layer toolpath length; t_c is the time allowance for corners and acceleration/deceleration; and t_s is the time for servicing, installation of embedded components, and inspection.

For an average layer length of 43.0 m, the pure travel time is 5.97 min. With an approximate allowance of 1.25 min, the total cycle is 7.22 min. This value must be compared with the permissible interlayer interval of the selected mixture. At stops, embedded-component

locations, and complex corners, the actual interval may exceed the average; the assessment must therefore use the maximum return time to the control point.

7.3. Equipment effectiveness and printing time

The theoretical flow rate cannot be maintained continuously because of mixture preparation, cleaning, minor stops, corner slowdowns, sampling, and corrective actions. Overall equipment effectiveness (OEE), comprising availability, performance, and quality yield, is used to account transparently for these losses.

$$OEE = A \cdot P \cdot Q_r \quad (5)$$

A is availability; P is the ratio of actual to nominal speed; and Q_r is the proportion of output requiring no rework.

$$t_p = V_p / (Q_{th} \cdot OEE) \quad (6)$$

t_p is the effective printing duration; V_p is the volume; and Q_{th} is the theoretical flow rate.

Table 12 — OEE and printing-duration calculation

Indicator	Value	Explanation
Availability A	0.85	Stops, washout, waiting for material
Performance P	0.90	Slowdowns, corners, nonprinting travel
Quality Q_r	0.97	No rework/rejection
OEE	0.742 (74.2 %)	Product of the three factors
Effective flow rate	0.289 m ³ /h	$Q_{th} \times OEE$
Printing duration	40.2 h	For $V_p = 11.61 \text{ m}^3$

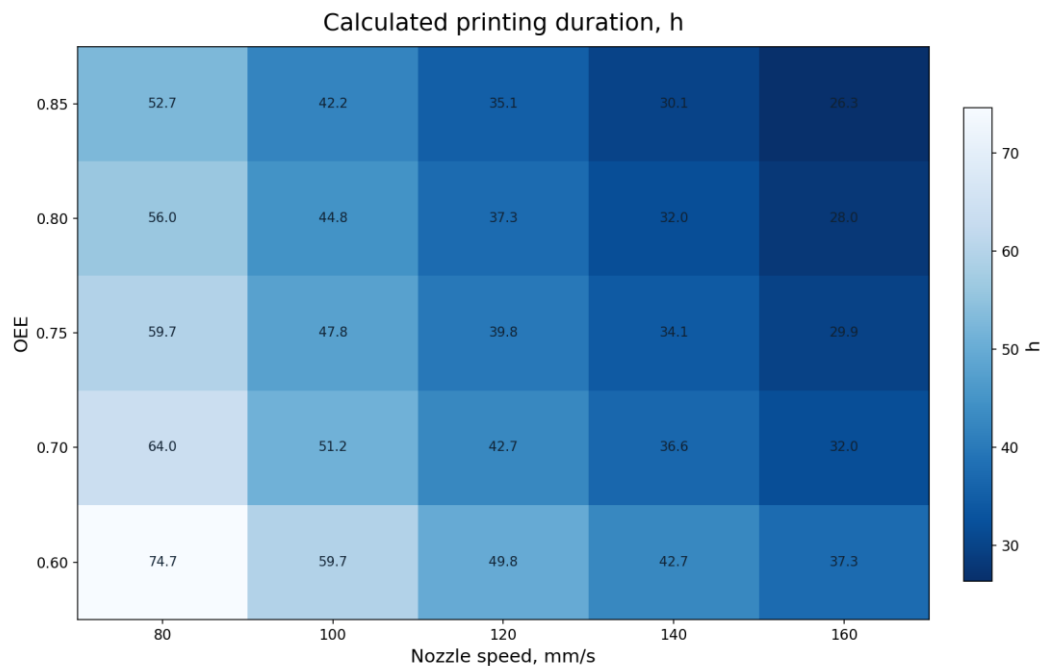


Figure 9 — Sensitivity of printing duration to nozzle speed and OEE

7.4. Green-strength constraint

During continuous build-up, the lower layer supports the weight of the fresh material above it. The approximate vertical action is estimated from density and

$$\sigma_v = \rho \cdot g \cdot H \quad (7)$$

σ_v is the vertical stress at the base of the fresh wall; ρ is density; and H is the continuous build height.

$$f_{\text{green}}(t) \geq \gamma_p \cdot \sigma_v \quad (8)$$

$f_{\text{green}}(t)$ is the green load-bearing resistance when height H is reached; γ_p is the process safety factor.

For a density of 2,100 kg/m³ and a continuous height of 3.0 m, the approximate stress is 61.8 kPa. With a factor of 2.0, the target resistance at the corresponding time

height, but the actual criterion must account for wall geometry, eccentricity, bulging, structuration, and the time-dependent development of strength.

must be at least 123.6 kPa. This value does not replace buildability and local-stability testing of the control specimen.

7.5. Production shifts and crew composition

Table 13 — Recommended print-cell shift crew

Role	Number	Primary responsibility
Printing supervisor/technologist	1	Start authorization, parameter assessment, stop decisions
Robot operator	1	Program, coordinates, safe cycle
Mixing-and-pumping-system operator	1	Batching, mixture, delivery, cleaning
Laboratory technician/quality inspector	1	Samples, bead geometry, specimens, records

Role	Number	Primary responsibility
Embedded-component/reinforcement installer	1–2	Installation of components at inspection hold points
Surveyor/scanning specialist	As required	Control points, intermediate and as-built surveys
BIM/CDE specialist	As required	Revisions, statuses, and compilation of the digital record

8. Construction Sequence and 4D Planning

8.1. Principle for developing the schedule

The schedule is based not only on operation durations, but also on process-quality dependencies. Printing does not begin until the survey control and bottom-support positions have been verified; the core is not filled until

the shells and embedded components have been inspected; the movement joint is not closed until free travel has been measured; and work does not proceed to the next story until an intermediate as-built model has been issued.

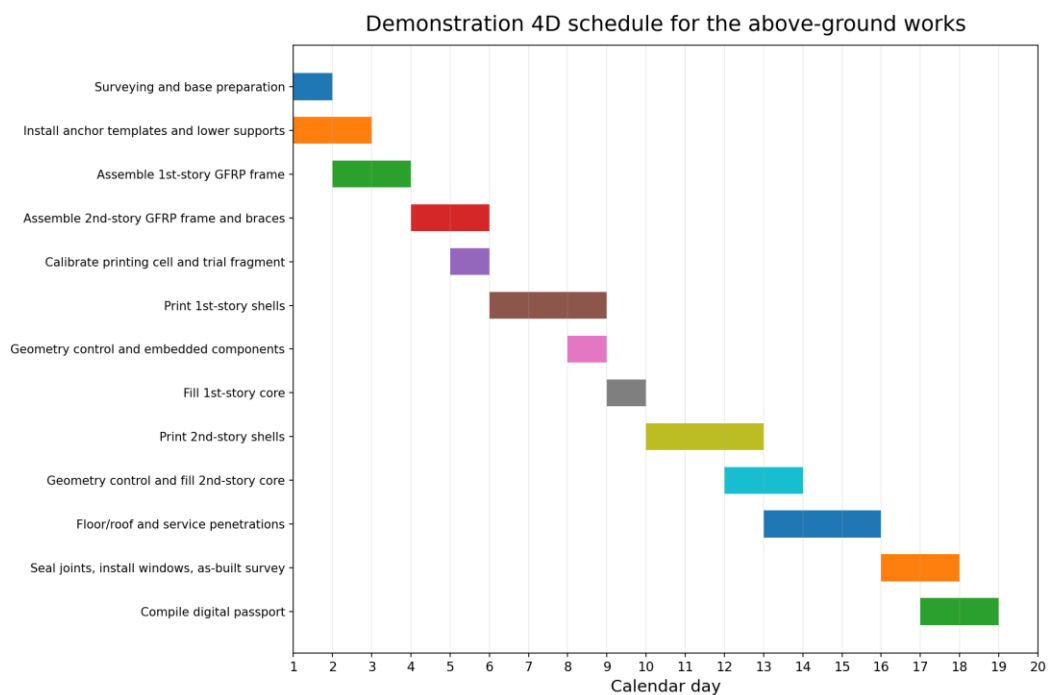


Figure 10 — Demonstration 18-day 4D schedule for the building superstructure

Table 14 — Key process dependencies

Preceding operation	Release outcome	Subsequent operation
Surveying and anchor templates	Coordinate and elevation report	Column erection
GFRP frame assembly	Geometry, tightening, bracing configuration	Print-cell setup
Trial print	G3 — acceptable geometry and specimens	Wall printing
Printing to an embedded-component location	Coordinate hold point	EMB installation

Preceding operation	Release outcome	Subsequent operation
Printing the story shell	Scanning and acceptance	Core filling
Core filling	Density and lift height	Closure of process openings
Sliding-anchor installation	Measured free travel	Joint sealing
As-built survey	Closed NCRs and complete data package	Handover of the digital passport

8.2. Preparation of the base and bottom supports

Before frame erection, survey control points, surface elevation, anchor-group coordinates, and planarity of the support zones are verified. The bottom supports of the printed wall are installed using a template and protected against accidental displacement. Their elevation governs the geometry of the first layer and distribution of wall self-weight; adjustment must therefore be completed before printing rather than compensated by changing the first-bead thickness.

8.3. Erection of the GFRP frame

Erection is performed story by story with temporary bracing. Components are supplied in kits for each erection work area. Bolts are tightened in accordance with the specified procedure, but final fixation of connections affecting geometry is performed after survey verification of the frame. Holes must not be enlarged using impact tools; any coordinate mismatch is registered as a nonconformance and requires an engineering disposition.

Table 15 — Erection control for the composite frame

Inspection item	Method	Demonstration-project criterion
Support elevation	Level survey	As specified in the detailed design; local adjustment without improvised shims
Column verticality	Total station/laser	Within the specified erection tolerance
Bay diagonals	Linear measurements	Consistency with BIM coordinates
Bolts and washers	Visual + instrumental	Complete set, correct orientation, torque/preload record
Hole edges	Visual	No new chips, cracks, or delamination
Bracing	Geometry and marking	Installed in accordance with the analytical configuration before temporary restraints are removed

8.4. Shell printing and installation of embedded components

Printing is performed in zones coordinated with the equipment work envelope and permissible interlayer interval. At each control height, the program stops, the nozzle position and actual geometry are verified, and the embedded component or process cross-tie is then installed. The operator must not shift an embedded component manually without recording the changed coordinate.

Openings are formed either by routing the toolpath around them with temporary support to the upper section, or by separate printing and installation of a lintel. The selected method must be qualified in advance. The

design clearance is maintained at interfaces with the frame; protective inserts prevent mortar from entering slotted holes and sliding surfaces.

8.5. Filling the polystyrene-concrete core

Filling is performed after the shell has reached its verified green strength and the lower zones have been checked for leak tightness. The height of each lift is limited by the pressure of the fresh fill and the shell load-bearing capacity investigated in Article 3. Density is controlled by batch and selected specimens, while the actual volume is compared with the calculated model quantity. Uneven filling around embedded components and openings is prevented by access openings and a controlled sequence.

8.6. Building-services penetrations and movement joints

Building-services penetrations should preferably be coordinated before printing. Subsequent drilling is permitted only in accordance with an approved map that excludes embedded components, anchors, and critical cross-ties. Before the movement joint is sealed, the actual free travel of the sliding connection is measured. The sealant, membrane, and finish must accommodate the design cyclic movement and must not create a rigid bridge between the wall and frame.

9. Quality-Control System and Release Gates

9.1. General principle

The quality plan follows the process-based principles of ISO 9001 and ISO 10005: inputs, responsibility, controlled characteristics, measurement method, frequency, criterion, record, and action in the event of nonconformance are defined for every operation [18–19]. In additive construction, the inspection record must be synchronized with process time and the identifier of the relevant wall zone.

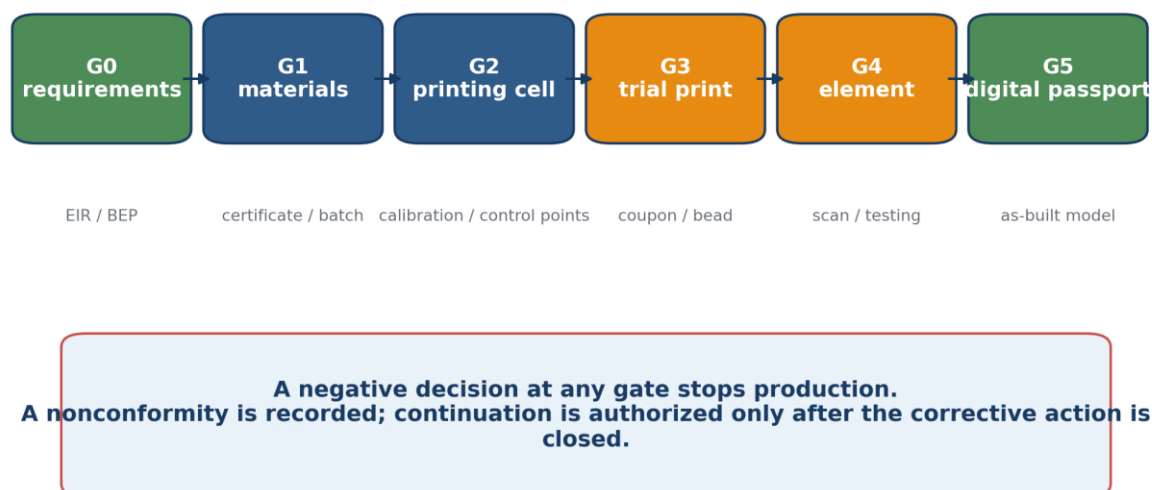


Figure 11 — Quality release gates G0–G5 for digital and physical production

Table 16 — Content of the quality release gates

Gate	Decision object	Minimum evidence	Decision
G0	Requirements and plan	EIR/BEP, responsibility matrix, acceptance criteria	Authorize design/preparation
G1	Materials and components	Certificates, batches, incoming tests, marking	Authorize use
G2	Print cell	Calibration, safety, control points, sensor verification	Authorize trial cycle
G3	Trial print	Geometry, continuity, buildability, specimens	Authorize production printing
G4	Element/story	Scan, embedded components, parameter log, closed NCRs	Authorize filling/the next work area

Gate	Decision object	Minimum evidence	Decision
G5	Building	As-built model, passports, certificates, reports, instructions	Handover to the client

9.2. Incoming inspection of materials and components

Incoming inspection is not limited to document review. For the print mixture, the identity of raw materials, aggregate moisture, admixture shelf life, and dispenser operability are verified. For GFRP profiles, the batch,

dimensions, straightness, surface condition, and conformity with the documentation are checked. The grade, coating, dimensions, and completeness of fasteners and metallic components are recorded.

Table 17 — Incoming inspection of principal materials

Material/product	Inspection	Frequency	Record
Cement and mineral constituents	Documents, batch, shelf life, storage conditions	Each delivery	Batch register
Aggregates/sand	Moisture and grading in accordance with the plan	Shift/batch	Laboratory log
Admixtures and fibers	Product designation, shelf life, dosage	Each batch	Data sheet and batching record
GFRP profiles	Dimensions, defects, marking	Each delivery + 100% visual inspection	Incoming-inspection certificate
Bolts, washers, sleeves	Size, grade, coating, certificate	Batch	Fastener register
Polystyrene concrete	Composition/constituents, target density	Batch	Mixture passport and specimens
Sealant and membranes	Compatibility, shelf life, movement capability	Batch	Material data sheet

9.3. In-process control of the printing process

In-process control comprises continuous, periodic, and event-triggered measurements. Pressure, speed, position, and time are recorded continuously. Bead geometry is checked by camera or by selective measurement after a

specified number of layers. Event-triggered inspection is performed after a stop, batch change, nozzle cleaning, weather change, or installation of an embedded component.

Table 18 — Controlled 3D-printing parameters

Characteristic	Method	Proposed frequency	Action on excursion
Volumetric flow rate	Sensor/calculation from mass and time	Continuous + batch reconciliation	Correction within the qualified range or stop
Nozzle speed and coordinates	Robot controller	Continuous	Safe stop in the event of mismatch
Bead width/height	Camera, laser, template	Continuous or every 5–10 layers	Adjust flow rate/speed; assess the affected zone
Interlayer interval	Toolpath time stamps	Every layer/control point	Change the sequence or issue a disposition for the cold joint

Characteristic	Method	Proposed frequency	Action on excursion
Mixture and ambient temperature	Sensors	Continuous/each batch	Adjustment of the processing window
Pump pressure	Sensor	Continuous	Check for blockage, hose condition, and rheology
Embedded-component position	Survey/template/camera	100 %	Do not continue printing until verified
Surface condition	Camera/visual	Continuous/by layer	Mark the defect and issue an NCR

9.4. Control specimens and representativeness

Control specimens must reproduce the layer direction and process interval of the actual wall. A combination of simultaneously printed coupons, extracted specimens, and, where required, cast reference specimens of the

mixture is recommended. Sampling is linked to a specific time range and wall zone. A cast specimen is used to control the material, but does not replace a printed specimen when assessing interlayer bond and anisotropy [44–48].

Table 19 — Minimum matrix of control specimens

Specimen	Purpose	Orientation/condition	Object link
Fresh mixture	Rheology, density, air content, temperature	At the mixer/nozzle outlet	MIX batch
Printed coupon	Geometry, buildability, green strength	Same layer and speed	Wall time interval
Extracted specimen	Strength and interlayer interface	In three directions where required	Wall/zone
Cast reference specimen	Baseline mixture properties	Standard molding	Material batch
Polystyrene-concrete specimen	Density, strength, thermal conductivity	Batch and fill height	CORE
Connection mock-up	Pull-out/bearing/travel/sealing	Design interface	Connection U2–U5

9.5. Geometric verification

Geometry is controlled at three scales. At bead level, width and height are measured. At wall-zone level, deviation from vertical, opening position, thickness, and embedded-component coordinates are checked. At

building level, the point cloud is registered in the common coordinate system and compared with the published BIM model. Particular attention is given not to the mean surface, but to critical interfaces: supports, anchor slots, openings, and junctions.

$$d_i = n_i \cdot (p_i - p_i^*) \quad (9)$$

d_i is the signed deviation of measured point p_i from the nearest design surface p_i^* along normal n_i .

$$RMSE = \sqrt{[(1/N) \cdot \sum d_i^2]} \quad (10)$$

RMSE is used as an overall indicator, but does not replace checks of the local maximum and systematic offset.

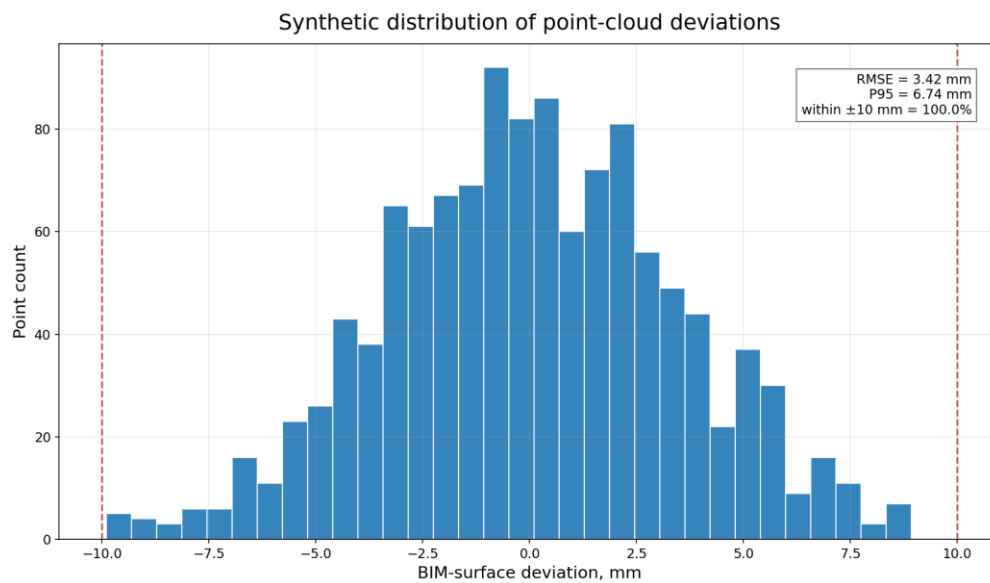


Figure 12 — Example statistical presentation of point-cloud-to-BIM-surface comparison results

Table 20 — Proposed geometric indicators for the report

Indicator	Purpose	Comment
Mean deviation	Systematic offset	May be small because of mutual cancellation
RMSE	Overall measure of dispersion	Sensitive to large deviations
P95 of absolute deviation	Robust characteristic of most of the surface	Convenient for an acceptance report
Maximum d	Local defect	Context and outliers must be checked
Proportion of points within tolerance	Clear indication of suitability	Must be supplemented by a deviation map
Deviation of critical coordinates	Openings, embedded components, connections	Takes precedence over overall statistics

9.6. Inspection of deformation-decoupled connections

For connections U2–U5, not only attachment strength but also kinematics are inspected. The slotted hole must have the specified length and orientation; the bolt must be in its initial design position; the washer must cover the

slot without clamping it; the protective insert must prevent mortar intrusion; and the sealant must retain its movement capacity. After installation, available movement is verified manually or instrumentally.

Table 21 — Acceptance inspection of a sliding connection

Parameter	Method	Criterion
Slot length and width	Caliper/template	As specified on the drawing and by the calculated travel

Parameter	Method	Criterion
Slot orientation	Visual/survey	Aligned with the direction of relative movement
Bolt position	Measurement of distances to slot ends	Initial reserve complies with the design
Free sliding	Proof movement/feeler gauge	No restraint by mortar, washer, or finishes
Out-of-plane restraint	Fastener completeness	The anchor transfers out-of-plane load
Sealing	Inspection and proof cycle of the mock-up	Continuous seal without rigid filling of the clearance
Photograph and ID	Digital record	100% of connections before closure

10. Digital Monitoring and Feedback

10.1. Data architecture

The data stream includes the robot controller, pump sensors, gravimetric dispensers, weather station, cameras, surveying instruments, and manual inspection records. All sources must use synchronized time. Raw

data are retained in an immutable archive, while aggregated indicators and alarms are displayed on the production dashboard. The acceptance decision references the underlying dataset rather than only the final chart.

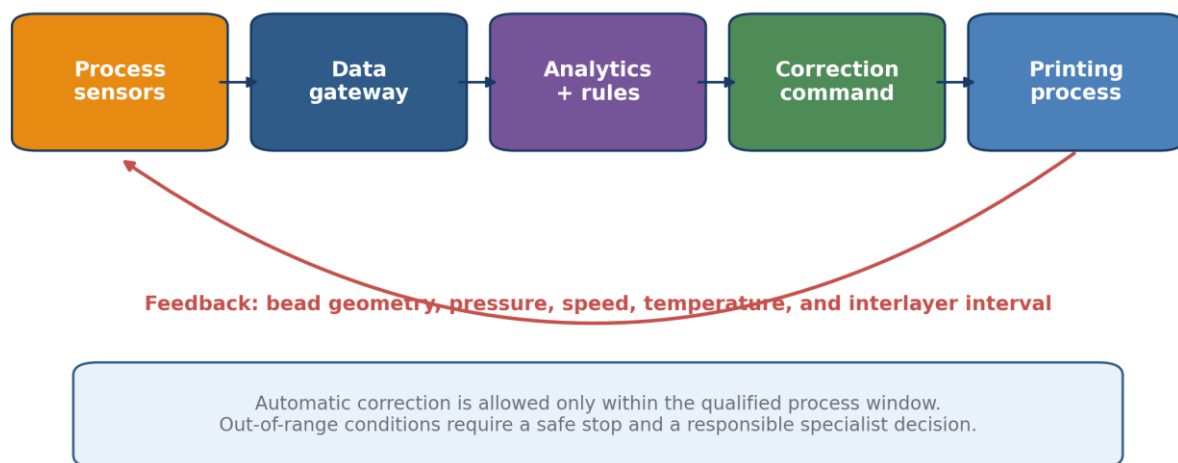


Figure 13 — Closed loop for monitoring, analytics, and corrective action

Table 22 — Recommended recording frequency and granularity

Source	Parameters	Frequency/event	Storage
Robot controller	XYZ, speed, program, status	10–100 Hz or system log	Raw log + layer-level aggregates
Pump/extruder	Pressure, flow rate, current/torque	1–10 Hz	Data stream + alarms

Source	Parameters	Frequency/event	Storage
Mixer/dispensers	Masses, time, sequence	Each batch	Batch passport
Weather station	Temperature, humidity, wind	1 min	Time series
Camera/depth sensor	Geometry, defects	Continuous/event frames	Images + extracted features
Survey/scanner	Coordinates/point cloud	At control heights and completion	Point cloud + comparison report
Manual inspection	Measurement, photograph, signature	In accordance with the ITP	INS/NCR form

10.2. Rules for automatic correction

Automatic correction is permissible for small bead-width deviations where the cause is unambiguous, the sensors are reliable, and the new speed-and-flow-rate combination remains within the qualified window.

Correction is not applied in the event of a sharp pressure rise, loss of coordinates, bead discontinuity, temperature excursion, significant settlement, or safety-system failure.

Table 23 — Example monitoring decision logic

Event	Automatic action	Human intervention required
Width below target at stable pressure	Slightly increase flow rate or reduce speed	Monitor the trend and confirm after several beads
Width above target	Reduce flow rate/increase speed within the qualified window	Assess bulging and wall displacement
Pressure rises while flow rate falls	Stop extrusion and move to a safe position	Check for blockage and verify rheology
Loss of coordinates/control point	Immediate safe stop	Repeat survey registration
Missed embedded component	Prevent continuation of the toolpath	Engineering disposition for remediation
Interlayer interval exceeded	Mark the potential cold joint	Decision on surface preparation/testing
Loss of data recording	Continue only to a safe stopping point	Restore the log; assess the completed zone

10.3. Completeness and quality of the digital record

The digital evidence base is itself a quality object. A missing time stamp or incorrect link to the wall identifier

can render an otherwise valid measurement unusable. A mandatory-data completeness index and a relationship-traceability index are proposed.

$$I_c = N_{\text{filled}} / N_{\text{required}} \cdot 100 \% \quad (11)$$

I_c is the completeness of mandatory fields for an element or quality gate.

$$I_t = N_{\text{linked}} / N_{\text{records}} \cdot 100 \% \quad (12)$$

I_t is the proportion of records correctly linked to the object, batch, time, and revision.

For G4 release, $I_c = 100\%$ is proposed for critical fields and $I_t \geq 98\%$ for the parameter stream; however, any missing data relating to embedded components, sliding

connections, or mixture batch are treated as critical regardless of the overall percentage.

11. Statistical Process Control and Tolerance System

11.1. Control chart for bead width

A single measurement demonstrates conformity at one point but does not reveal process drift. A control chart

can detect a systematic change in flow rate, nozzle wear, rheological change, or a shift in nozzle-to-layer distance. In the synthetic demonstration dataset of 36 measurements, the mean width is 45.01 mm and the standard deviation is 0.56 mm.

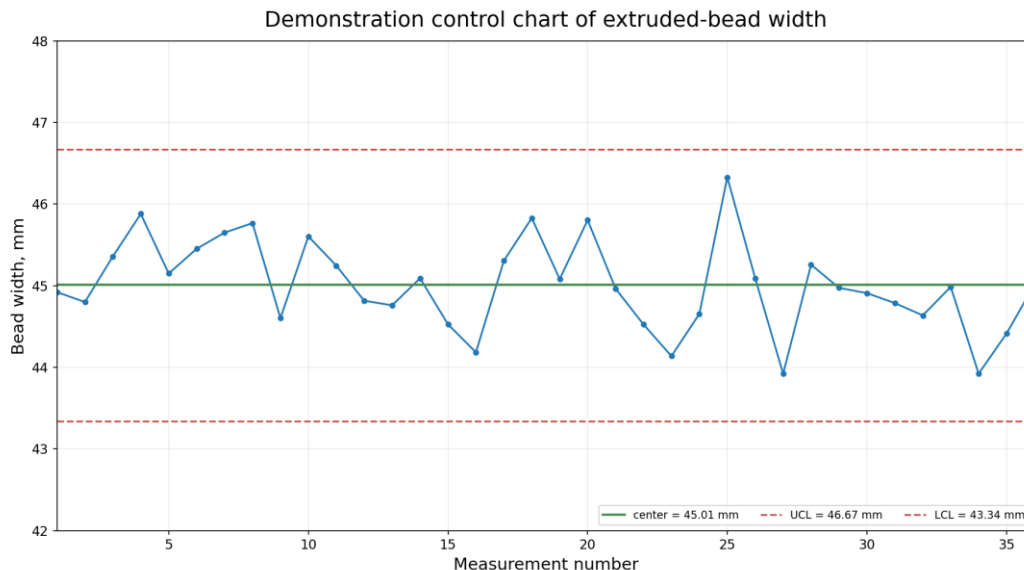


Figure 14 — Demonstration control chart for extruded-bead width

$$C_{pk} = \min\left[\frac{(USL - \mu)}{(3s)}, \frac{(\mu - LSL)}{(3s)}\right] \quad (13)$$

Cpk evaluates the ability of a stable process to remain between the upper and lower specification limits.

For the assumed limits of 42–48 mm, the demonstration Cpk is 1.79. A value above 1.33 indicates adequate capability for the example considered, but is not a result of actual qualification. Before construction, the index must be determined from a series of trial prints under a stable process rather than from selectively edited data.

$$T_{RSS} = \sqrt{(t_1^2 + t_2^2 + \dots + t_n^2)} \quad (14)$$

T_{RSS} is the statistical estimate of the resultant tolerance for independent components.

$$T_{WC} = \sum |t_i| \quad (15)$$

T_{WC} is the worst-case estimate; it is used for safety-related functions and where statistical distributions are unknown.

11.2. Tolerance stack-up at a critical interface

The position of the sliding connection depends on deviations of the frame, printed wall, embedded component, bracket slot, and survey registration. Even where every component complies with its individual tolerance, an unfavorable combination may reduce free travel. The root-sum-square method is used for independent random components, while the arithmetic sum is used for a guaranteed worst-case assessment.

Table 24 — Demonstration tolerance budget for a sliding anchor

Source of deviation	Tolerance, mm	Inspection
GFRP column axis	±4	Survey after erection
Printed-surface position	±6	Scanning
Embedded-component coordinate	±3	Template + photograph/scan
Bracket-slot fabrication	±1	Caliper
Fastener installation	±2	Measurement of bolt position
RSS total	±8.1	For statistical assessment
Worst-case total	±16.0	For conservative travel verification

11.3. Point-cloud processing example

A synthetic set of 1,200 deviations was generated to demonstrate the algorithm. The resulting values are RMSE = 3.42 mm, P95 of absolute deviation = 6.74 mm, and 100.0% of points within ±10 mm. These values do not characterize the actual printer accuracy; they illustrate the report structure. Acceptance must additionally address local zones and systematic offset.

12. Risk Management and Work Safety

12.1. Process FMEA

FMEA is used to rank potential failures by severity S, occurrence O, and difficulty of detection D. The risk priority number RPN does not replace engineering judgment: an event with high severity may require a barrier even where its probability is low. For critical functions—personnel safety, embedded-component position, connection free travel, and robot coordinates—the principle that no single latent failure is acceptable is applied [20–21].

$$RPN = S \cdot O \cdot D \quad (16)$$

S, O, and D are rated on the adopted corporate scale from 1 to 10.

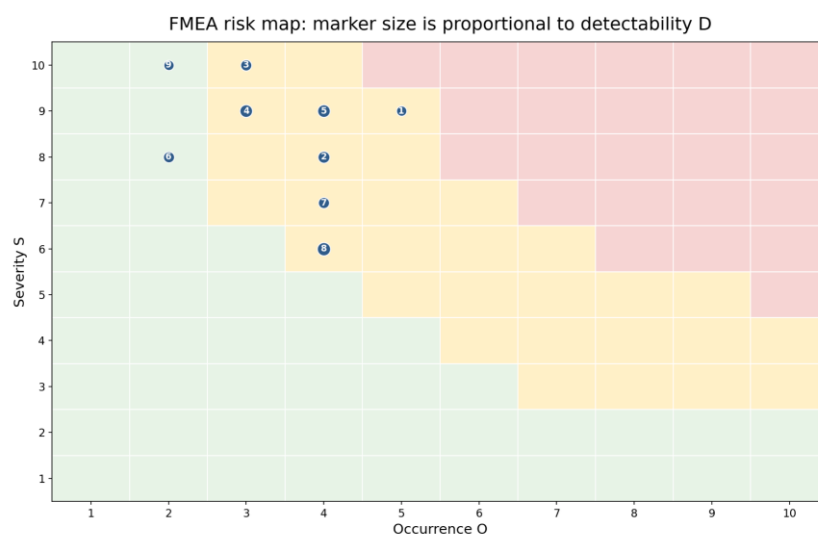


Figure 15 — Demonstration FMEA risk map for the construction technology

Table 25 — Selected risks and control measures

Nº	Failure	S/O/D	RPN	Principal measures
1	Unstable mixture delivery	9/5/4	180	Flow sensor, pressure monitoring, backup mode, and stop
2	Excessive interlayer interval	8/4/6	192	Layer-time calculation, toolpath optimization, cold-joint marking
3	Shift of the robot zero point	10/3/5	150	Dual survey verification and a dry-run control toolpath
4	Omission of an embedded component	9/3/7	189	Digital checklist, programmed stop, and 100% photographic record
5	Mortar filling of a slotted hole	9/4/7	252	Protective inserts, pre-closure inspection certificate, and free-travel check
6	Incorrect GFRP profile batch	8/2/5	80	QR marking and verification of the kit against the BIM register
7	Insufficient polystyrene-concrete density	7/4/5	140	Mass/volume control, density specimens, controlled lift sequence
8	Loss of monitoring data	6/4/8	192	Local data redundancy and prohibition on continuing a critical operation
9	Personnel present in the robot zone	10/2/4	80	Guarding, interlocks, area scanners, and emergency stop

12.2. Print-cell safety

ISO/ASTM 52939:2023 does not replace occupational-safety requirements or safety requirements for robotic equipment. The print zone must be physically guarded or protected by a certified access-control system; entry by personnel must inhibit automatic motion. Emergency stops, a safe pressure-relief state for the pump, hose-rupture protection, electrical-connection checks, dust

extraction for dry materials, and safe washout procedures must be provided [15, 20].

ISO 19650-6:2025 extends information management to health-and-safety information. For the project, this means linking hazardous zones, heavy components, lifting points, chemical hazards, access restrictions, and instructions to model objects so that the information is available during planning and on site [8].

12.3. Mandatory stop conditions

Table 26 — Events requiring a mandatory safe stop

Event	Reason for stopping	Condition for restart
Person enters the protected zone	Risk of collision with the robot	Reset the interlock after inspecting the zone
Loss of coordinates or position mismatch	Risk of departing from the geometry/impacting the frame	Recalibration and dry-run toolpath
Pressure spike/material-delivery interruption	Risk of hose damage and bead defect	Cleaning, mixture verification, and trial extrusion
Loss of buildability	Risk of progressive collapse of fresh layers	Isolate the affected zone and obtain the technologist's decision

Event	Reason for stopping	Condition for restart
Weather outside the qualified range	Unpredictable rheology/evaporation	Restore conditions or provide protective enclosure
Omission of a critical embedded component	Standard connection cannot be executed	Approved engineering disposition
Loss of a mandatory record	Loss of traceability	Recover the data or reject the indeterminate zone

13. Results of the Demonstration Computational-Process Analysis

13.1. Quantities and production rate

For a net external-wall area of 172.8 m², the calculated volume of print mortar is 11.61 m³. Under the baseline

parameters, the theoretical flow rate is 0.389 m³/h and, at OEE = 0.742, the effective flow rate is 0.289 m³/h. The calculated shell-printing duration is 40.2 h. The total toolpath reaches 12.90 km; consequently, even a small systematic width error significantly affects material consumption and surface position.

Table 27 — Summary results of the process calculation

Indicator	Value
Net wall area	172.8 m ²
Print-mortar volume	11.61 m ³
Core volume	31.59 m ³
Number of layers	300
Toolpath length	12.90 km
Average layer cycle	7.22 min
OEE	74.2 %
Effective flow rate	0.289 m ³ /h
Printing duration	40.2 h
Demonstration calendar cycle	18 days

13.2. Influence of OEE and speed

The parametric analysis shows that increasing nozzle speed without improving process stability does not guarantee a shorter actual duration. For example, a higher nominal speed may be accompanied by reduced quality, more stops, and increased rework. The target indicator should therefore be defined as the effective volume of conforming material produced per hour rather than the maximum instantaneous speed.

Within the range considered, reducing OEE from 0.80 to 0.60 increases printing time by 33%. A similar effect occurs when speed is reduced from 120 to 90 mm/s. This supports prioritizing preventive maintenance, stable

mixture logistics, and rapid inspection before attempting to increase speed.

13.3. Influence of the tolerance system on free travel

The statistical combination of the demonstration installation components is approximately ±8.1 mm, while the worst-case arithmetic total is ±16 mm. For a connection with one-sided travel of approximately 38 mm, this tolerance budget is significant. The geometric accuracy of the wall and frame must therefore be managed jointly, and the actual bolt position must be verified before sealing. Nominal slot length alone does not demonstrate the availability of the required free movement.

13.4. Digital readiness for acceptance

The proposed G0–G5 scheme transforms the document package from a final archive into an active production-control mechanism. Critical records are generated before the element is closed, while any defect remains accessible for correction. Persistent identifiers make it possible to select a wall or connection in the model and retrieve its linked history: design revision, batch, toolpath, parameter log, photographs, scan, and acceptance decision.

14. Qualification and Experimental Verification Program

14.1. Verification levels

The technology cannot be validated by a single trial wall alone. A hierarchical program is proposed in which each level answers a distinct question: whether the material is suitable for delivery and structuration; whether the process reproduces the geometry; whether the connection retains strength and kinematics; whether the wall subassembly withstands filling and service actions; whether the pilot module validates integration; and whether the digital passport provides traceability.

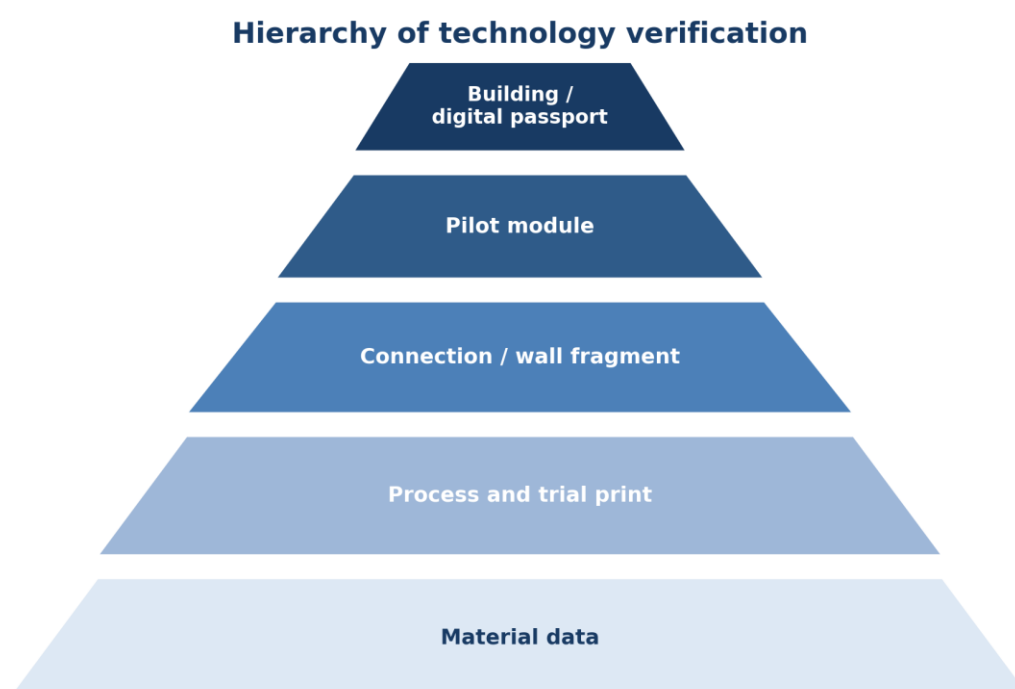


Figure 16 — Hierarchy of process qualification and verification

Table 28 — Qualification-test program

Level	Test/check	Key result
Material	Rheology, density, temperature, structuration	Qualified time window
Extrusion	Series of beads at different v and Q values	Process map for geometry and stability
Trial wall	Build-up, corners, stop/restart, embedded components	Buildability and repeatability
Hardened material	Directional strength, interlayer bond, shrinkage	Design and control properties
GFRP connection	Bearing, slip, tightening torque, cyclic movement	Load-bearing capacity and failure mode

Level	Test/check	Key result
Wall connection	Anchor pull-out, free travel, sealing	Frame–wall compatibility
Core-filled subassembly	Filling pressure, thermal performance, moisture	Safe lift height and service properties
Pilot module	Complete production cycle and scanning	Validation of the 4D workflow and digital thread

14.2. Preliminary acceptance criteria for the pilot section

Table 29 — Proposed criteria for the pilot section

Criterion	Preliminary requirement	Basis for refinement
Extrusion continuity	No discontinuities or voids affecting the cross-section	Visual/camera inspection and cut sections
Bead width	Target value $\pm$ specified tolerance; stable process	Trial series and geometry calculation
Layer height	Within the qualified window	Toolpath and scan
Interlayer interval	Not greater than the value validated for the required bond	Coupon tests
Wall deviation	As specified in the detailed design; critical interfaces checked separately	Scanning
Embedded-component position	100% of coordinates within tolerance	Survey/template/model
Connection free travel	Not less than the calculated demand plus reserve	Measurement before closure
Completeness of critical data	100 %	Automated CDE audit
NCR closure	100% before transition through G4/G5	Corrective-action register

14.3. Calibration of the digital model using pilot data

After the pilot print, calculated time norms, OEE, cross-tie factor, actual consumption, permissible interval, distribution of geometric deviations, and labor inputs are replaced with measured values. BIM objects receive validated property templates, and the 4D schedule is updated with actual dependencies. The original demonstration version and change log must be retained to avoid retrospective adjustment without an evidence base.

15. Discussion of Results

15.1. Technology as a system of interfaces

The principal outcome is not a single production-rate value, but a structure for managing interfaces. The GFRP frame and printed wall have different production natures: the former is assembled from a discrete factory-fabricated kit, whereas the latter is formed by a

continuous time-dependent process. Compatibility is achieved through a common survey coordinate system, standardized identifiers, and verifiable connections. An error in any one of these three components may become apparent only during installation; digital coordination must therefore precede the physical operation.

15.2. Why strength control alone is insufficient

Specimen strength is necessary, but does not confirm embedded-component position, absence of a cold joint, preservation of a slot, geometric accuracy, or stability of the complete batch. Likewise, a visually sound bead does not guarantee interlayer bond or green stability. The quality plan therefore integrates material, process, geometry, interface, and data. This is consistent with the process-oriented approach of ISO/ASTM 52939 and current quality-control roadmaps for printed concrete [15, 44–48].

15.3. Limitations of the calculation example

The calculation is based on approximate geometry, an assumed opening ratio, an internal cross-tie factor, a rectangular bead model, and the adopted OEE. Actual robot accelerations, corner toolpaths, reinforcement stops, rheological changes in the hose, weather enclosures, and specific logistics are not included. The 18-day duration is not a commercial commitment and serves as a basis for subsequent 4D calibration.

Synthetic control samples do not replace statistics from actual printing. Tolerances, Cpk, and alarm thresholds must be established after measurement uncertainty has been determined and the equipment qualified. For critical connections, a conservative worst-case approach is preferable until validated distributions have been accumulated.

15.4. Practical implementation

For a pilot project, implementation should begin with a limited set of digital objects: GFRP profile, connection, print zone, mixture batch, embedded component, control specimen, and NCR. Once these operate reliably, sensor streams, automated point-cloud comparison, and analytics can be added. This phased approach reduces the risk of deploying a complex platform before actual decisions and responsibilities have been defined.

Practical implementation principle

The solution and responsibilities should be standardized first, the record should then be digitized, and only afterward should control be automated. Automation does not correct an undefined process; it merely reproduces its strengths and weaknesses more rapidly.

16. Conclusions

1. An integrated construction technology has been developed for a low-rise building with a pultruded GFRP frame and three-layer 3D-printed walls, combining information modeling, DfMA, robotic printing, erection, inspection, and as-built documentation.
2. A digital thread—"requirement—object—operation—inspection record—acceptance decision"—is proposed. A persistent identifier links geometry, material, batch, toolpath, parameters, specimens, photographs, point cloud, and as-built revision.
3. The information organization is aligned with the principles of ISO 19650, open IFC exchange under ISO 16739-1:2024, the level of information need under ISO 7817-1:2024, and data templates

under ISO 23387:2025. A project-specific property set, Pset_3DCP_Process, is proposed for the printing process.

4. For the demonstration building, the net wall area is 172.8 m², the print-mortar volume is 11.61 m³, and the polystyrene-concrete core volume is 31.59 m³. At parameters of 20 × 45 mm, a speed of 120 mm/s, and OEE = 0.742, the calculated printing duration is approximately 40.2 h.
5. A demonstration 18-day 4D schedule has been developed in which transitions among erection, printing, installation of embedded components, core filling, and sealing are governed by quality release gates rather than by calendar sequence alone.
6. A plan for incoming, in-process, and acceptance inspection has been developed, including monitoring of flow rate, pressure, speed, bead geometry, interlayer interval, environmental conditions, embedded-component position, control-specimen properties, surveying, and the condition of movement-accommodating connections.
7. It is shown that tolerance stack-up among the frame, wall, embedded component, and fastener can substantially reduce nominal free travel. The kinematic function of the sliding connection must therefore be measured directly before it is concealed by finishes.
8. Statistical control and computer vision should be used for early detection of process drift; however, automatic correction is permissible only within the qualified processing window. Loss of coordinates, buildability, a critical embedded component, or a mandatory record requires a safe stop.
9. A hierarchical verification program is proposed: material → extrusion → trial wall → hardened properties → GFRP connection → wall interface → core-filled subassembly → pilot module → digital passport.
10. Before publication or design application, all demonstration parameters must be replaced with data for the selected printing system, recipes, profiles, connections, and site, and the effectiveness of the technology must be validated through a pilot construction module.

References

1. Decree of the President of the Republic of Uzbekistan No. UP-151 dated August 28, 2023,

- “On Measures for the Effective Organization of Public Administration in Construction and Housing and Utility Services within the Framework of Administrative Reforms.”
2. Resolution of the President of the Republic of Uzbekistan No. PP-104 dated March 13, 2026, “On Measures to Improve the Effectiveness of the System for Comprehensive Review of Predesign and Procurement Documentation.”
 3. Resolution of the Cabinet of Ministers of the Republic of Uzbekistan No. 231 dated April 23, 2024, “On Measures to Bring Regulatory Instruments into Conformity with International Standards in the Construction Sector.”
 4. ShNK 1.05.01, “Building Information Modeling. Rules for Organizing the Work of Production and Technical Departments”—a document included in the list of standards to be improved under Resolution of the Cabinet of Ministers of the Republic of Uzbekistan No. 231 dated April 23, 2024; the status and details of the approved edition must be verified before publication.
 5. ISO 19650-1:2018. Organization and Digitization of Information about Buildings and Civil Engineering Works, Including Building Information Modelling (BIM) — Information Management Using Building Information Modelling — Part 1: Concepts and Principles. Geneva: ISO, 2018.
 6. ISO 19650-2:2018. Organization and Digitization of Information about Buildings and Civil Engineering Works, Including BIM — Information Management Using BIM — Part 2: Delivery Phase of the Assets. Geneva: ISO, 2018.
 7. ISO 19650-4:2022. Organization and Digitization of Information about Buildings and Civil Engineering Works, Including BIM — Information Management Using BIM — Part 4: Information Exchange. Geneva: ISO, 2022.
 8. ISO 19650-6:2025. Organization and Digitization of Information about Buildings and Civil Engineering Works, Including BIM — Information Management Using BIM — Part 6: Health and Safety Information. Geneva: ISO, 2025.
 9. ISO 16739-1:2024. Industry Foundation Classes (IFC) for Data Sharing in the Construction and Facility Management Industries — Part 1: Data Schema. Geneva: ISO, 2024.
 10. ISO 7817-1:2024. Building Information Modelling — Level of Information Need — Part 1: Concepts and Principles. Geneva: ISO, 2024.
 11. ISO 23386:2020. Building Information Modelling and Other Digital Processes Used in Construction — Methodology to Describe, Author and Maintain Properties in Interconnected Data Dictionaries. Geneva: ISO, 2020.
 12. ISO 23387:2025. Building Information Modelling (BIM) — Data Templates for Objects Used in the Life Cycle of Assets. Geneva: ISO, 2025.
 13. ISO 21597-1:2020. Information Container for Linked Document Delivery — Exchange Specification — Part 1: Container. Geneva: ISO, 2020.
 14. ISO 29481-1:2025. Building Information Models — Information Delivery Manual — Part 1: Methodology and Format. Geneva: ISO, 2025.
 15. ISO/ASTM 52939:2023. Additive Manufacturing for Construction — Qualification Principles — Structural and Infrastructure Elements. Geneva: ISO, 2023.
 16. ISO/ASTM 52900:2021. Additive Manufacturing — General Principles — Fundamentals and Vocabulary. Geneva: ISO, 2021.
 17. ISO/ASTM 52950:2021. Additive Manufacturing — General Principles — Overview of Data Processing. Geneva: ISO, 2021.
 18. ISO 9001:2015. Quality Management Systems — Requirements. Geneva: ISO, 2015.
 19. ISO 10005:2018. Quality Management — Guidelines for Quality Plans. Geneva: ISO, 2018.
 20. ISO 45001:2018. Occupational Health and Safety Management Systems — Requirements with Guidance for Use. Geneva: ISO, 2018.
 21. ISO 31000:2018. Risk Management — Guidelines. Geneva: ISO, 2018.
 22. ASCE/SEI 74-23. Load and Resistance Factor Design (LRFD) for Pultruded Fiber Reinforced Polymer (FRP) Structures. Reston, VA: ASCE, 2023. DOI: 10.1061/9780784415771.
 23. CEN/TS 19101:2022. Design of Fibre-Polymer Composite Structures. Brussels: CEN, 2022.
 24. ASTM D3917-12(2019). Standard Specification for Dimensional Tolerance of Thermosetting Glass-Reinforced Plastic Pultruded Shapes. West Conshohocken, PA: ASTM International, 2019.
 25. García-Alvarado R., Soza P., Moroni G., Pedreros F., Avendaño M., Banda P., Berrios C. From BIM Model to 3D Construction Printing: A Framework

- Proposal // *Frontiers of Architectural Research*. 2024. Vol. 13, No. 4. P. 912–927. DOI: 10.1016/j.foar.2024.03.002.
26. Smarsly K., Peralta Abadia P., Luckey D., Hein S.S.V., Ludwig H.M. BIM-Based Concrete Printing // *Proceedings of the 18th International Conference on Computing in Civil and Building Engineering (ICCCBE 2020). Lecture Notes in Civil Engineering*. 2020. Vol. 98. P. 992–1002. Cham: Springer. DOI: 10.1007/978-3-030-51295-8_69.
 27. Peralta Abadia P., Smarsly K. An Algorithmic BIM Approach to Advance Concrete Printing // *Proceedings of the 28th International Workshop on Intelligent Computing in Engineering (EG-ICE 2021)*. 2021. DOI: 10.14279/depositonce-12021. ISBN: 978-3-7983-3212-6.
 28. Buswell R.A., Leal de Silva W.R., Jones S.Z., Dirrenberger J. 3D Printing Using Concrete Extrusion: A Roadmap for Research // *Cement and Concrete Research*. 2018. Vol. 112. P. 37–49. DOI: 10.1016/j.cemconres.2018.05.006.
 29. Mechtcherine V., Bos F.P., Perrot A., da Silva W.R.L., Nerella V.N., Fataei S., Wolfs R.J.M., Sonebi M., Roussel N. Extrusion-Based Additive Manufacturing with Cement-Based Materials — Production Steps, Processes, and Their Underlying Physics: A Review // *Cement and Concrete Research*. 2020. Vol. 132. Art. 106037. DOI: 10.1016/j.cemconres.2020.106037.
 30. Bos F., Wolfs R., Ahmed Z., Salet T. Additive Manufacturing of Concrete in Construction: Potentials and Challenges of 3D Concrete Printing // *Virtual and Physical Prototyping*. 2016. Vol. 11, No. 3. P. 209–225. DOI: 10.1080/17452759.2016.1209867.
 31. Le T.T., Austin S.A., Lim S., Buswell R.A., Gibb A.G.F., Thorpe T. Mix Design and Fresh Properties for High-Performance Printing Concrete // *Materials and Structures*. 2012. Vol. 45. P. 1221–1232. DOI: 10.1617/s11527-012-9828-z.
 32. Le T.T., Austin S.A., Lim S., Buswell R.A., Law R., Gibb A.G.F., Thorpe T. Hardened Properties of High-Performance Printing Concrete // *Cement and Concrete Research*. 2012. Vol. 42, No. 3. P. 558–566. DOI: 10.1016/j.cemconres.2011.12.003.
 33. Perrot A., Rangeard D., Pierre A. Structural Built-Up of Cement-Based Materials Used for 3D-Printing Extrusion Techniques // *Materials and Structures*. 2016. Vol. 49. P. 1213–1220. DOI: 10.1617/s11527-015-0571-0.
 34. Roussel N. Rheological Requirements for Printable Concretes // *Cement and Concrete Research*. 2018. Vol. 112. P. 76–85. DOI: 10.1016/j.cemconres.2018.04.005.
 35. Panda B., Chandra Paul S., Mohamed N.A.N., Tay Y.W.D., Tan M.J. Measurement of Tensile Bond Strength of 3D Printed Geopolymer Mortar // *Measurement*. 2018. Vol. 113. P. 108–116. DOI: 10.1016/j.measurement.2017.08.051.
 36. Wolfs R.J.M., Bos F.P., Salet T.A.M. Hardened Properties of 3D Printed Concrete: The Influence of Process Parameters on Interlayer Adhesion // *Cement and Concrete Research*. 2019. Vol. 119. P. 132–140. DOI: 10.1016/j.cemconres.2019.02.017.
 37. Quah T.K.N., Tay Y.W.D., Lim J.H., Tan M.J., Wong T.N., Li K.H.H. Concrete 3D Printing: Process Parameters for Process Control, Monitoring and Diagnosis in Automation and Construction // *Mathematics*. 2023. Vol. 11, No. 6. Art. 1499. DOI: 10.3390/math11061499.
 38. Kazemian A., Yuan X., Davtalab O., Khoshnevis B. Computer Vision for Real-Time Extrusion Quality Monitoring and Control in Robotic Construction // *Automation in Construction*. 2019. Vol. 101. P. 92–98. DOI: 10.1016/j.autcon.2019.01.022.
 39. Lao W., Li M., Tjahjowidodo T. Improving Surface Finish Quality in Extrusion-Based 3D Concrete Printing Using Machine Learning-Based Extrudate Geometry Control // *Virtual and Physical Prototyping*. 2020. Vol. 15, No. 2. P. 178–193. DOI: 10.1080/17452759.2020.1713580.
 40. Ahi O., Ertunç Ö., Başaran Bundur Z., Bebek Ö. Automated Flow Rate Control of Extrusion for 3D Concrete Printing Incorporating Rheological Parameters // *Automation in Construction*. 2024. Vol. 160. Art. 105319. DOI: 10.1016/j.autcon.2024.105319.
 41. Zhang H., Tan Y., Hao L., Zhang S., Xiao J., Poon C.S. Intelligent Real-Time Quality Control for 3D-Printed Concrete with Near-Nozzle Secondary Mixing // *Automation in Construction*. 2024. Vol. 160. Art. 105325. DOI: 10.1016/j.autcon.2024.105325.
 42. Jhun J., Lee D.H., Rehman A.U., Kang S., Kim J.H. Development of a Real-Time Geometric Quality Monitoring System for Extruded Filaments of 3D Concrete Printing Construction // *IEEE Access*. 2024. DOI: 10.1109/ACCESS.2024.3401472.

43. Senthilnathan S., Raphael B. Using Computer Vision for Monitoring the Quality of 3D-Printed Concrete Structures // Sustainability. 2022. Vol. 14, No. 23. Art. 15682. DOI: 10.3390/su142315682.
44. Wolfs R., Bos D., Caron J.-F., Gerke M., Mesnil R., Buswell R., et al. On-Line and In-Line Quality Assessment across All Scale Levels of 3D Concrete Printing // Cement and Concrete Research. 2024. Vol. 185. Art. 107646. DOI: 10.1016/j.cemconres.2024.107646.
45. Mechtcherine V., Van Tittelboom K., Kazemian A., Kreiger E., Nematollahi B., Nerella V.N., Santhanam M., De Schutter G., Van Zijl G., Lowke D., et al. A Roadmap for Quality Control of Hardening and Hardened Printed Concrete // Cement and Concrete Research. 2022. Vol. 157. Art. 106800. DOI: 10.1016/j.cemconres.2022.106800.
46. Bos F., Menna C., Robens-Radermacher A., et al. Mechanical Properties of 3D Printed Concrete: A RILEM TC 304-ADC Interlaboratory Study — Approach and Main Results // Materials and Structures. 2025. Vol. 58. Art. 183. DOI: 10.1617/s11527-025-02686-x.
47. Wolfs R., Versteeg J., Santhanam M., et al. Mechanical Properties of 3D Printed Concrete: A RILEM TC 304-ADC Interlaboratory Study — Flexural and Tensile Strength // Materials and Structures. 2025. Vol. 58. Art. 182. DOI: 10.1617/s11527-025-02687-w.
48. Robens-Radermacher A., Kujath C., Bos F., Mechtcherine V., Unger J.F. Mechanical Properties of 3D Printed Concrete: A RILEM TC 304-ADC Interlaboratory Study — Design and Implementation of a Database System for Querying, Sharing, and Analyzing Experimental Data // Materials and Structures. 2025. Vol. 58. Art. 184. DOI: 10.1617/s11527-025-02650-9.
49. Wang Y., Aslani F., Dyskin A., Pasternak E. Digital Twin Applications in 3D Concrete Printing // Sustainability. 2023. Vol. 15, No. 3. Art. 2124. DOI: 10.3390/su15032124.
50. Pučko Z., Šuman N., Rebolj D. Automated Continuous Construction Progress Monitoring Using Multiple Workplace Real-Time 3D Scans // Advanced Engineering Informatics. 2018. Vol. 38. P. 27–40. DOI: 10.1016/j.aei.2018.06.001.